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Eddington limited starbursts in the central 10 pc of AGN, and the Torus in NGC 1068

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Abstract. We present results from a survey of nearby AGN using the near infrared adaptive optics integral field spectrograph SINFONI. These data enable us to probe the distribution and kinematics of the gas and stars at spatial resolutions as small as $0.085''$. We find strong evidence for recent but short lived starbursts residing in very dense nuclear disks; on scales of less than 10 pc these would have reached Eddington-limited luminosities when active, perhaps accounting for their short duration. In addition, for NGC 1068 at a resolution of 6 pc, we present direct observations of molecular gas close around the AGN which we identify with the obscuring torus.

1. Introduction

We have mapped the distribution and kinematics of the gas and stars in 9 nearby AGN using adaptive optics to reach high spatial resolution at near infrared wavelengths. The AGN are mostly Seyfert 1s, of which 2 are ULIRGs and 1 a QSO. The primary goals of the project are to: (i) determine the extent and history of star formation, and its relation to the AGN and torus; (ii) measure the properties of the molecular gas, and understand its relation to the torus; (iii) derive black hole masses from spatially resolved stellar kinematics. Detailed studies of several individual objects are already published: Mkn 231 (Davies et al. 2004a); NGC 7469 (Davies et al. 2004b); Circinus (Mueller Sánchez et al. 2006); NGC 3227 (Davies et al. 2006a). Additionally, we are analysing the general properties of the star formation (Davies et al., in prep) and the molecular gas (Hicks et al. in prep). In this contribution, we highlight 2 pertinent features of the H_2 in NGC 1068 and summarise our results about nuclear star formation.

2. Molecular Gas in NGC 1068

NGC 1068 is a prototypical Seyfert 2 galaxy and one of the cornerstones of AGN unification schemes. Yet, despite its proximity to us (14.4 Mpc, $1'' = 70$ pc), many aspects of its nuclear region remain poorly understood. In particular, it is now apparent from our SINFONI H_2 1–0 S(1) data that simple warped disk models of the molecular gas (Schinnerer et al. 2000; Baker 2000) cannot account for the fantastic variety and detail in the morphological and kinematical

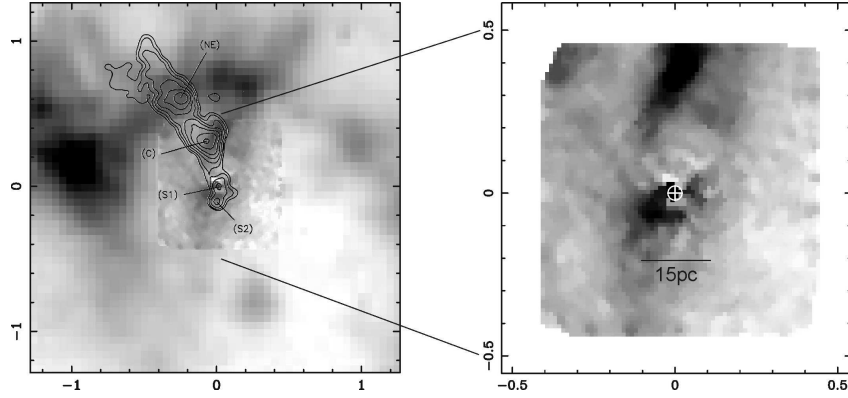


Figure 1. H_2 1-0 S(1) line emission in NGC 1068. Left: square-root scaling, with a 5 GHz radio continuum image (Gallimore et al. 1996) overlaid showing that the jet brightenings coincide with the presence of H_2 ; Right: the central arcsec at a resolution of 85 mas, showing the finger of emission to the north and the central clump of emission identified as the torus.

structure (see Davies et al. 2006b). Here we focus on the two aspects apparent in Fig. 1, which are discussed in more detail by Mueller Sánchez et al. (in prep).

2.1. Jet/Cloud Interaction

Radio Continuum imaging at 5 GHz with a resolution of $0.065''$ revealed a number of structures along the inner part of the radio jet (Gallimore et al. 1996). Associating component S1 with the inner edge of the torus, these authors developed a scenario in which component C arises from a shock interaction between the jet and a dense molecular cloud. Supporting this hypothesis was the bend in the radio jet, the slightly flatter spectral index, and the presence of maser emission. The left-hand panel in Fig. 1 shows that component C does in fact coincide spatially with a finger of 1-0 S(1) emission which traces H_2 . Moreover, the $v = 1$ levels are thermalised, indicating that the gas is likely to be rather dense ($> 10^4 \text{ cm}^{-3}$). Thus the SINFONI data provide direct evidence for the molecular cloud and hence strongly support the jet-cloud interaction hypothesis. Interestingly, the jet component NE occurs where the jet crosses an arc of brighter 1-0 S(1) emission, suggesting that it may also result from an interaction between the jet and molecular gas although perhaps not in a head-on collision as appears to be the case at component C.

2.2. The Torus

The right-hand panel of Fig. 1 reveals that close around the position of the near infrared non-stellar continuum, which indicates the location of the AGN, we have detected an extended clump of 1-0 S(1). Since the 1-0 S(1) directly traces H_2 , we associate this clump with the molecular material responsible for obscuring the AGN. There are 2 crucial pieces of evidence to support this: (i) the 1-0 S(1) emission is oriented at a position angle of $\sim 120^\circ$, consistent with that of the line of maser spots (Greenhill et al. 1996), the 20 mas scale radio

continuum in the nuclear component S1 (Gallimore et al. 2004), and the 300 K dust emission (Jaffe, this proceedings); (ii) the size scale is remarkably similar to those of static torus models, in particular the more realistic clumpy model of Hönig et al. (2006), for which a size of 15×7 pc (diameter) is predicted for the H_2 distribution (Hönig, this proceedings). This then appears to be the first direct image of the torus in NGC 1068.

3. Nuclear Star Formation in AGN

In evolving stellar populations, once late type stars appear, the equivalent widths of the CO 2-0 $2.29 \mu\text{m}$ and CO 6-3 $1.62 \mu\text{m}$ bandheads stay approximately independent of age. Thus, while these features can say nothing about the stellar population itself, they facilitate the important step of separating the stellar continuum from the non-stellar continuum associated with the AGN. They also enable one to measure the kinematics of the stars – by convolving a suitable stellar template with a broadening function, which is optimised so as to minimise the difference between the galaxy spectrum and the convolution product. Without any additional modelling of the stellar age or history, these simple measures already yield significant insights into the nuclear stellar population.

3.1. Spatially Resolved Nuclear Disks

NGC 1068 and NGC 1097 show the clearest evidence for distinct nuclear stellar populations from both the surface brightness profile and the kinematics. At larger radii (i.e. out to a few arcsec), the surface brightness profile can be well fit by a single $r^{1/4}$ profile. But when this is convolved with the PSF and extrapolated inwards, one finds excess stellar continuum at radii less than 0.5 – $1''$. Similarly, at larger radii, the velocity dispersion is 120 – 150 km s^{-1} ; but as one approaches the nucleus it decreases, reaching 70 – 100 km s^{-1} at the centre. Sigma-drops have been seen in several spiral galaxies, and are interpreted as arising from gas accretion into the central regions followed by star formation (Emsellem 2006). Because the gas is dynamically cool, so will the newly formed stars be: in contrast to the spheroidal bulge, their distribution will be rather disk-like. We have now spatially resolved 2 of these sigma-drops, and shown that they are associated with excess stellar continuum – strong evidence in favour of their being a distinct dynamically cool stellar population. In these specific cases, we are able to trace this population to radii of ~ 50 pc, and estimate a mass of order $10^8 M_\odot$. Under the assumption that they are self-gravitating, this implies a vertical scale height of 5 – 10 pc suggesting that these nuclear disks are in fact relatively thick and that random motions still provide significant support.

3.2. Luminous Young Starbursts

Making a rough estimate of the bolometric luminosity L_{bol} from the K-band luminosity L_K is possible without knowing in detail the star formation history. This is because $L_{\text{bol}}/L_K \sim 60$ to within a factor 3 (for ages exceeding 10 Myr). Detailed modelling of the stellar populations has in fact been performed for the AGN listed in Section 1. More generally, making careful corrections for contributions from the AGN and its associated phenomena, it is possible to

constrain the age using the Br γ flux, the supernova rate (estimated from radio continuum measurements in the literature), the K-band stellar luminosity, and the dynamical mass. Doing so, we find for our sample of AGN characteristic ages in the range 10–300 Myr.

Looking at how L_{bol} varies as a function of radius, we find that our sample of AGN all follow a similar trend which we are able to trace from scales of 1 kpc down to only a few parsecs. The surface brightness increases at smaller radii, approaching $10^{13} L_{\odot} \text{ kpc}^{-2}$ on scales of a few parsec. This is the surface brightness predicted by models of optically thick star forming disks in ULIRGs by Thompson et al. (2005). The difference is that in ULIRGs it extends over a size scale of 1 kpc; in these AGN the most intense starburst is confined to the central few parsec.

Thompson et al. (2005) argued that ULIRGs are essentially Eddington limited starbursts. The reason is that their bolometric luminosity per unit mass is similar to the $500 L_{\odot}/M_{\odot}$ which Scoville (2003) argued is sufficient for radiation pressure to halt further accretion. Within the central few tens of parsecs, the AGN we have observed are an order of magnitude below this limit. Intriguingly, the typically low Br γ fluxes imply that although the star formation is recent, it is no longer active. This is important because short-lived starbursts fade very quickly: the bolometric luminosity L_{bol} of a burst which is active for a timescale of 10 Myr will have decreased by more than an order of magnitude at an age of 100 Myr. Thus in the recent past, these nuclear stellar populations could easily have been 10 times more luminous than at present – in which case they would have been radiating at the Eddington limit for starbursts.

Our analysis indicates that intense but short-lived starbursts are likely to be common close around AGN. It may be that whether one is able to detect the signature of such starbursts in AGN depends on the time-scales and size-scales which are being probed by the observations.

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